Monitoring of Air Contaminant Gases Using a UV-Based Optical Sensor

Payali Das
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi, India
payali.das@ee.iitd.ac.in

Ebha Deepti Singh
Electronics and Communication Engineering
GLA University
Mathura, India
ebha.singh13@gmail.com

Swades De
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi, India
swadesd@ee.iitd.ac.in

Shouri Chatterjee
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi, India
shouri@ee.iitd.ac.in

***Abstract*—This paper presents the development and evaluation of an ultraviolet (UV) based optical gas sensor module for air pollution monitoring applications. The proposed system is capable of accurately measuring concentrations of nitrogen dioxide (NO2), ozone (O3), and sulphur dioxide (SO2) by exploiting the principles of light absorption and scattering. Comparative analysis with data from the reference sensor demonstrates a strong correlation, validating the reliability and accuracy of the designed gas sensor module. Unlike traditional electrochemical gas sensors, which necessitate a complex analog front end (AFE) to detect gas concentrations, our designed module offers a more cost-effective solution with enhanced sensitivity and a compact design. This paper elucidates the working principle, design considerations, and experimental results of the proposed gas sensor module, highlighting its advantages over conventional sensors.**

Keywords—UV, optical sensor, gas sensing, air contaminants

I. Introduction

Gas sensors will remain in high demand in the future, as they are indispensable for solving and mitigating various gas-related problems through continual advancements [1]. Gas sensors can be classified into direct and indirect types. Direct sensors measure gas concentrations directly in the gas phase, providing real-time analysis. Indirect sensors generate an analytical signal through gas interaction with an active surface [2]. Some common examples of direct gas sensors include electrochemical sensors, photoionization detectors, infrared gas sensors, and UV spectroscopy-based gas sensors. Indirect gas sensors encompass technologies such as metal oxide semiconductor (MOS) sensors, catalytic bead sensors, and thermal conductivity detectors.

UV absorption spectrometry is known for its high sensitivity and reliability, making it a valuable approach for gas sensing. It provides self-referenced measurements and selective detection, ensuring accurate and precise results in gas analysis. In recent years, UV absorption spectrometry has found various applications in the detection and analysis of gases such as NO_2, O_3, SO_2, and aromatic organic compounds. The development of portable UV absorption spectrophotometers has been facilitated by incorporating LEDs, hollow core waveguides (HCW), and UV photodetectors [3].

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Addressing air pollution requires both emergency response measures and long-term structural solutions, including prioritizing air pollution control, establishing robust air quality monitoring systems, implementing effective pollution reduction strategies, and providing accurate information to the public, all aimed at creating cleaner and healthier environments. In the UV-visible spectrum, important gases like BTEX compounds, NO_X compounds, ozone, H_2S, and SO_2 exhibit strong absorption. UV-visible spectroscopy is a useful technique for identifying and monitoring these gases. An increasing need exists for a cost-effective air quality monitoring solution that provides significant advantages. UV Spectroscopy serves as an illustrative example, offering the potential for accurate measurements while remaining affordable [4]–[6].

A. Related Works

Sensors must exhibit sensitivity, selectivity, and real-time monitoring to ensure reliable air quality monitoring. It is essential for the sensors to be well-designed both electronically and mechanically [6].

The work in [1] presents Semiconductor gas sensors that are highly suitable for gas detection due to their simple device structure and circuitry and their ability to provide high sensitivity in detecting target gases. [3] proposed that in absorption spectrophotometry, high sensitivity is typically achieved by using a longer optical path length and substances that have strong absorption cross-sections. [7] introduced gas sensing in the mid-infrared wavelength range offering remarkable sensitivity and accuracy when it comes to rapidly detecting minute concentrations of molecular gases. The spectroscopy introduced by Chen et al. [8] Optical-distance spectroscopy based on a multi-reflection air chamber holds significant potential in the field of multi-gas detection using infrared spectroscopy due to its ultrahigh detection sensitivity and straightforward operation. Photoacoustic spectroscopy (PAS) is a valuable technique for detecting trace gases, which finds application in areas like food safety, atmospheric chemistry, and breath analysis. It is a widely recognized spectroscopic method due to its notable sensitivity [9], [10]. Authors in [11] introduced the limitations of NDIR (Non-Dispersive Infrared) technology, such as sensor accuracy and sensitivity, which have been addressed through various improvements. These include enhancements in measuring gas concentrations at the inlet, advancements in infrared sources, optical designs (including optical filters and gas chambers), as well as detector upgrades. In [12], the authors developed a novel nanofiber (NF) sensor capable of meeting these criteria using only one sensing element. The sensor operates on the principles of stimulated Raman scattering spectroscopy. Given the growing significance of hydrogen as both an energy carrier and industrial resource, there is a growing demand for hydrogen sensors that possess enhanced sensitivity.

Gas sensor technology originated in Japan with the introduction of three types of sensors: oxide semiconductor gas sensors for gas leakage alarms, solid electrolyte oxygen sensors for car emission control systems, and ceramic humidity sensors for automatic cooking ovens. These sensors highlighted the importance of real-time, continuous, and on-site monitoring of specific gases for safety, environmental protection, and improved functionality of home appliances [1]. The work in [2] proposed that UV and MIR absorption spectroscopy, which are direct-based sensors, are employed in certified reference analyzers installed in air quality units. These sensors enable real-time monitoring of ozone levels in the environment. Khan et al. [3] describe the need for portable gas analyzers that can provide real-time analytical data is increasing. These analyzers are expected to have high sensitivity, low consumption of pure gas (such as carrier gas), and low power requirements. The TRIAGE project aims to develop an intelligent, compact, and cost-effective network of air quality sensors as discussed in [7] work. According to [10], in situ monitoring and analysis employ analytical techniques for local determination of pollutant concentrations.

B. Motivation and Contribution

Air quality monitoring and maintenance plays an essential role in human health, environmental sustainability, and overall well-being. However, traditional methods for air quality monitoring are often restrained by their complexity and time-consuming nature, which limits their efficiency and practicality. While traditional methods like gas analyzers [3], reference monitoring stations [4], and filter-based sampling [5] etc. have been used for years, emerging technologies like UV spectroscopy-based gas sensors offer improved sensitivity, selectivity, and real-time monitoring capabilities at low-cost instrumentation. Compared to the electrochemical sensors which exhibit limited shelf life and poor sensitivity because of the chemical reaction between the target gas and electrode, the optical sensor performs better as they use specific wavelengths of light to detect gas concentrations, and their response is generally selective and can cover a wide range of gases. Optical sensors can offer high selectivity since they can be designed to target specific gas molecules' absorption or scattering characteristics. This makes them suitable for detecting multiple gases with minimal cross-sensitivity. Optical sensors can be more robust in harsh environments, as they are less affected by humidity and environmental contaminants. In our work, we have designed a UV-based, low-cost, high-accuracy gas-sensing module for monitoring of NO_2, O_3, and SO_2.

II. UV Spectrosopy

UV spectroscopy-based gas sensor is a specialized device that utilizes UV spectroscopy principles to detect and measure gases in the air. It operates by analyzing the absorption of UV light by gas molecules, allowing for the identification and quantification of specific gases present in the environment. UV spectroscopy-based gas sensors contribute by providing enhanced detection, real-time monitoring, selectivity, cost-effectiveness, versatility, and integration with IoT technologies, ultimately improving air quality monitoring and promoting human health and environmental sustainability. UV spectroscopy is a non-destructive technique that allows for continuous and repeated measurements without altering or depleting the sample. UV spectroscopy-based gas sensors are beneficial for air quality monitoring. They are very sensitive and can detect even small amounts of gases at low levels. These sensors can also distinguish between different gases, making it easier to accurately identify and measure specific pollutants.

The main application of UV absorption in gas sensing is the detection of ambient ozone (O_3) at 254 nm. While stratospheric ozone is essential for protecting life from harmful UV radiation, tropospheric O_3 at ground level can pose a threat to human health and plant growth. UV spectroscopy enables the accurate measurement of tropospheric O_3 concentrations, providing valuable data for air quality monitoring and pollution control efforts. Another significant gas that can be detected using UV spectroscopy is sulphur dioxide (SO_2), which absorbs at 275 nm. SO_2 is a harmful gas that can adversely affect the respiratory system, particularly lung function. By leveraging UV spectroscopy, it becomes convenient to detect and quantify SO_2 levels in the atmosphere, aiding in the assessment and mitigation of air pollution.

Additionally, UV spectroscopy allows for the detection of nitrogen dioxide (NO_2), which absorbs at 425 nm. NO_2 exposure is associated with various adverse effects on the respiratory system. Short-term exposure to NO_2 has been shown to have a linear association with an increased risk of death, including cardiovascular and respiratory complications. The ability to detect NO_2 concentrations accurately through UV spectroscopy is crucial for monitoring air quality in urban environments and industrial areas.

In Section III, the paper discusses the detailed process of detecting these three gases using UV spectroscopy. By exploiting the unique absorption characteristics of each gas at specific UV wavelengths, the gas sensor module can provide real-time and accurate measurements of NO_2, O_3, and SO_2 concentrations. The integration of UV spectroscopy in the gas sensor module enhances its capabilities for air pollution monitoring applications, enabling the detection of harmful gases and facilitating data-driven pollution control strategies.

III. Gas Sensor Prototype Design

As discussed in Section I-A, various methods for detecting gas contaminants in the air exist, but some of these approaches, such as NDIR-based systems, have drawbacks such as high energy consumption and manufacturing costs. In this study, we propose a gas sensor module that utilizes UV spectroscopy with low-power, cost-effective UV light sources (LEDs), and detectors to detect ozone (O_3), sulphur dioxide (SO_2), and nitrogen dioxide (NO_2). Unlike NDIR technology, which employs high-power Xenon light sources for light scattering, our gas sensor module utilizes UV LED light scattering principles. The block diagram of the sensor system is presented in Fig. 1. The gas sensor module design directs UV light from LEDs towards the gas particles, and a photodetector measures the light absorbed or dispersed by these particles. An Analog Front End (AFE) interfaces with the photodetector to process the output signal, which is then further analyzed through signal processing techniques. The UV LEDs and photodetectors are powered separately to avoid cross-detection of gases. The designed prototype is shown in Fig. 2. The fan is used to blow ambient air inside the sensor chamber and likewise, there is an air outlet at the backside of the module to keep the chamber.

IV. Results and Discussion

In this section, we present the experimental results of our UV spectroscopy-based gas sensor prototype for the detection of NO_2, ozone O_3, and SO_2 concentrations. The prototype was deployed on the IIT Delhi campus for a duration of ten days, during which a total of 432 samples were collected at a sampling interval of 30 minutes. The choice of a 30-minute sampling interval was based on the understanding that gas parameters do not change rapidly over short time intervals. This interval allowed us to obtain sufficient data points for a comprehensive analysis while balancing data resolution and storage requirements. The collected data was stored locally before further processing and analysis. To assess the data quality and validate the accuracy of our designed sensor, we used reference data obtained from the CPCB RK Puram station, as referenced in [13]. This reference station is located approximately 3 kilometres away on a highly polluted freeway, providing a comparison with our campus deployment in a relatively less polluted environment.

Fig. 3 illustrates the comparison between the readings obtained from our designed UV sensor and the reference sensor. Remarkably, the UV sensor data exhibits a close alignment with the trend of the reference sensor data. This strong correlation between the two datasets serves as a compelling validation of the reliability and accuracy of our gas sensor prototype. Fig. 4 shows the cross-correlation between the designed UV sensor data and the reference sensor data. It is noteworthy that the deployment of our sensor on the IIT Delhi campus, characterized by a less polluted environment compared to the reference station, resulted in relatively lower concentration values. Despite this difference, the consistent correspondence between our sensor's readings and the

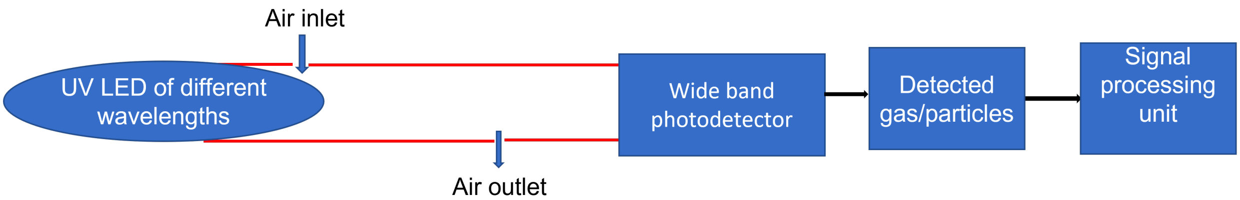

Fig. 1. Block diagram of the gas sensing module.

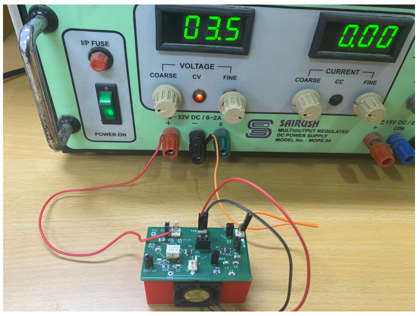

Fig. 2. Designed gas sensor prototype.

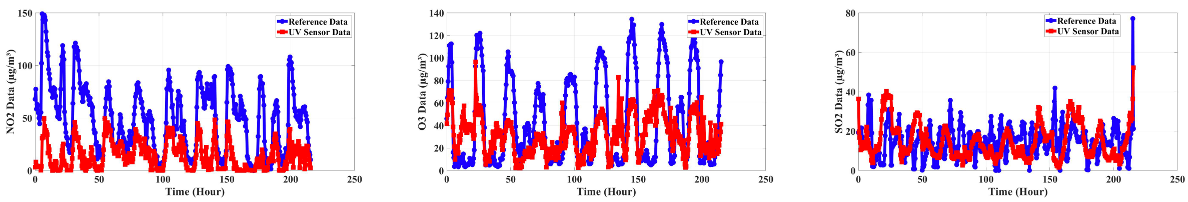

Fig. 3. NO_2, O_3, and SO_2 data collected by the designed UV spectroscopy-based sensor plotted against the reference data.

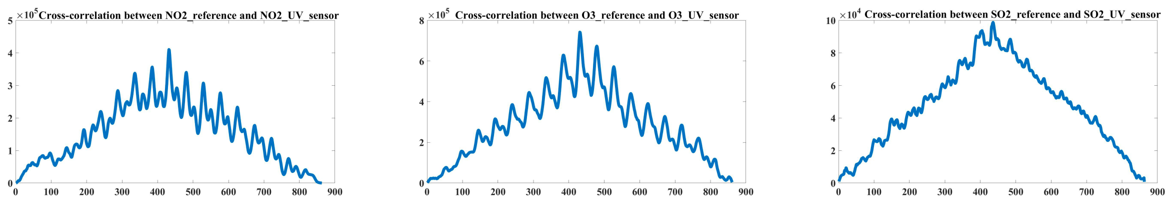

Fig. 4. Cross-correlation between the NO_2, O_3, and SO_2 data collected by the designed UV spectroscopy-based and the reference data.

reference sensor's data confirms the robustness of our designed gas sensor module.

The successful demonstration of the prototype's performance in tracking pollutant trends and its close agreement with the reference data further supports the suitability of our UV spectroscopy-based gas sensor for air pollution monitoring applications. By providing accurate and real-time pollutant measurements, our gas sensor module holds immense potential for enhancing air quality monitoring networks, contributing to informed decision-making, and enabling effective pollution control measures. Overall, the experimental results emphasize the promising capabilities of our UV spectroscopy-based gas sensor prototype and encourage its potential integration into comprehensive air quality monitoring systems.

V. Concluding Remarks

This paper highlights the potential of the optical spectroscopy-based gas sensor module as a cost-effective, sensitive, and reliable solution for air pollution monitoring applications. The reduced complexity of the AFE significantly reduces manufacturing costs, making the developed module a more cost-effective solution for widespread deployment in air quality monitoring networks. The module's enhanced sensitivity allows for the detection of low gas concentrations, a crucial aspect in accurately monitoring pollutant levels in various environments. The compact design of the gas sensor module further enhances its practicality, enabling seamless integration into existing air quality monitoring infrastructures. By offering improved accuracy, reduced manufacturing costs, and enhanced sensitivity, this technology represents a valuable contribution to the field of air pollution monitoring. Further, we are working to use this module in a fully developed self-sustainable air pollution monitoring device [14] and the focus will be on auto-calibration of the sensors.

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